Accuracy of Ocean Color Data Derived from the Coastal Zone Color Scanner (CZCS)

(2)

G. D. Hickman
S. C. Gallegos
Remote Sensing Branch
Ocean Sensing and Prediction Division
Ocean Science Directorate

M. J. Duggin
State University of New York

Approved for public release; distribution is unlimited. Naval Oceanographic and Atmospheric Research Laboratory, Stennis Space Center, Mississippi 39529-5004.

Abstract

The U.S. Navy is interested in investigating the use of ocean color data for naval applications, as they apply within the Air Defense Initiative. The major source of available data for assessment is the Coastal Zone Color Scanner (CZCS) data base. These data were collected during 1979-1986. Although the CZCS is no longer operational, much information has been published on the analysis of the data. This technical note reviews that literature, which deals primarily with the measured and estimated errors associated with using the CZCS data to derive either chlorophyll concentrations (C) or the diffuse attenuation coefficient (K) of oceanic waters.

The recognized uncertainties in the absolute values of the quantities of C and K must be taken into account when addressing the potential use of CZCS data for certain naval applications. The literature generally agrees that on a global basis, K or C can be determined from CZCS data to only within a factor of 2, as compared with in situ measurements. In addition, the water-leaving radiance for one spectral band can probably be obtained from the CZCS data, but in a more regional or smaller geographical area, after corrections to within $\pm$15%. This percentage relates to an error of approximately $\pm$30% in K or C, both of which use a ratio of at least two spectral bands. Extreme care must be taken in applying the appropriate corrections on a pixel-to-pixel basis if the error is to be reduced to this value. If the concern is with only spatial trends of water clarity at a particular point in time or with temporal trends at each point in space, the CZCS images can probably be used; however, the conditions under which they apply must be indicated.

A preliminary computer simulation that focuses on the impact of some of the data errors is also included with this review. Further modeling could lead to improved atmospheric corrections, leading to required statistical variances of the pixel radiance values as a function of geographical region and spectral band.

Acknowledgments

This work was supported by the Air Defense Initiative (ADI) under program management of Dr. Gerald Morris (program element 063741D) and the Oceanographer of the Navy, under program management of LCDR W. A. Cook (program element 63704N) Space and Naval Warfare Systems Command, Satellite Applications and Techniques program.

I. Introduction

The Coastal Zone Color Scanner (CZCS), flown on the NIMBUS-7 satellite, collected ocean color data from July 1979 to June 1986. This scanning radiometer viewed the ocean in six coregistered spectral bands; five in the reflective region of the spectrum (centered at 443, 520, 550, 670, and 750 nm) and one in the thermal IR (10.5 to 12.5 μm). Although the CZCS data has contributed enormously to our knowledge of the world's oceanic productivity, its data is known to include errors. Many of these errors are associated with radiometric sensitivity of the instrument, exact derivation of the pigment concentration, the effect of subpixel sized clouds on the retrieved radiances, complete removal of the atmospheric turbidity, and navigational errors to cite a few.

This technical note summarizes the results of a number of key technical reports concerned with the errors associated with comparing in situ ocean color measurements with those derived from satellite CZCS data. A fairly comprehensive bibliography has been included.

A preliminary computer based sensor error model was constructed and presented in section IV. It is given to illustrate the potential value of using a modeling approach to assess the nature and impact of various environmental parameters on the total error budget of the CZCS data.

II. Satellite Derived Ocean Color Data

A. Algorithms for correlating satellite and in situ measurements

"Ocean Color" is a measure of the spectral reflectance of the water column. It is measured remotely as the wavelength-dependent radiance emerging from the sea surface. Ratios of water leaving radiance are used to calculate phytoplankton pigment concentration. Research using CZCS data has established the feasibility of using ocean color observations from space to study global and mesoscale distributions of ocean bio-optical properties. The CZCS data has been used extensively for its potential ability to map global distributions and standing stock of marine phytoplankton.

The "diffuse attenuation coefficient" ($K(\lambda)$)is a quantity that has been extensively used as a measure of water quality or visibility. This quantity is of primary importance to those naval applications that are concerned with operation of active and passive optical sensors.

Smith and Baker (1978; 1982) related the spectral diffuse attenuation coefficient ($K(\lambda)$) to chlorophyll pigment concentrations (C), while Clark (1981) derived an algorithm relating ($C\bar{\lambda}$), to the upwelling radiances Lw(443) and Lw(550) given below

$$K(490) = 0.0883 \cdot \left[\frac{Lw(443)}{Lw(550)}\right]^{-1.491} + 0.022 \qquad (1)$$

Austin and Petzold (1981) in their classic article on this subject related the upwelling radiances at Lw(443) and Lw(550), and (C) through the following empirical expressions

$$C^{\bar{\lambda}} = 0.766 \cdot \left[\frac{Lw(443)}{Lw(550)}\right]^{-1.329} \qquad (2)$$

$$K(490) = 0.119 \cdot \left[\frac{\bar{\lambda}}{C}\right]^{1.122} + 0.022 \quad (3)$$

where:

Lw(443) = inherent upwelling radiance at 443 nm at the ocean surface
Lw(550) = inherent upwelling radiance at 550 nm at the ocean surface
$C\lambda$ = average chlorophyll pigment concentration in mg m^{-3}.

These algorithms were developed using CZCS data and in situ spectroradiometric data from 88 oceanographic stations from a large number of investigators working in a wide variety of water types. They concluded that it should be possible, under most field conditions, to infer values of C or K from satellite ocean color measurements with accuracies comparable with that of in situ measurements. They also stated that this was very dependent upon one's ability to make the appropriate atmospheric corrections.

B. Correlation of satellite derived and in situ surface chlorophyll concentrations

Gordon et al. (1980) compared CZCS and surface distributions and in situ pigment concentrations in the Gulf of Mexico during a Nimbus-7 post launch experiment in November 1979. They found that in the worst case the pigment concentration (C) could be estimated from radiance ratios to within a factor of 2, and the ratio of the radiances of Lw(443)/Lw(550) was useful only for pigment concentrations of less than 0.6 mg m^{-3} (K=0.089-equation 3). A number of papers appeared as a result of the South African Ocean Color and Upwelling Experiment for the time period November 1978 through April 1980. (Shannon et al., 1985; Walters, 1985; and Walters et al., 1985) The results of these studies showed that chlorophyll concentrations can be derived from CZCS radiance data with an accuracy of better than a factor of 2.

Muller-Karger et al. (1990) examined 21 CZCS images of the Southeastern Bering Sea to map the near-surface distribution of phytoplankton during 1979 and compared the results to in situ measurements made from the ship. They found that the CZCS data underestimated the ship data in chlorophyll pigment concentration by a factor of at least 2 during the spring of 1979. During a similar period of time in 1980 the two sets of data agreed much better. They concluded that region specific pigment algorithms may be required to yield quantitative results from remote sensing data—at least from the Bering Sea. Similarly, even at more moderate latitudes, the sun elevation may be sufficiently low in the winter to give rise to large errors in the inferred values of pigment concentrations.

Gordon et al. (1983a) compared CZCS data with ship data taken aboard the RV Athena II NOAA - NESS CZCS ocean color cruise (May 31, 1979 - June 23, 1979) from the Gulf of Maine to Florida. The results showed that the CZCS derived values for C reflected a ±30-40% difference with in situ values of C within the pigment concentration range 0.08 -1.5 mg m^{-3}. These results were obtained for regions showing relatively weak horizontal gradients, i.e., horizontal scale of variability significantly greater than the CZCS pixel size. A total of four images of the shelf and slope waters of the Middle Atlantic Bight and the Sargasso Sea were processed and averaged. The satellite derived values of C were compared with in situ values obtained from continuous measurements made from ships. The quoted errors are rms values.

Gordon and Clark (1981) presented data comparing in situ pigment concentrations and upwelling radiance for 60 Case I water sites off the west and east coasts of the U.S. and the Gulf of Mexico. (Case I waters are defined as those waters for which phytoplankton and their detrital material play the dominant role in determining the optical properties. The majority of open ocean waters can be classed as Case I. The results showed that a ±20% error existed in the upwelling radiance (in one band) which results in an approximate error in the pigment concentration (C) of ±40% for concentrations less than 0.25 mg m^{-3}.

C. Determination of water clarity to depth via CZCS data

The above discussion has dealt mainly with the measurement of phytoplankton pigment concentrations in the near surface water column; however, in many naval applications one is more concerned with the interpretation of satellite data to yield light penetration to depth. As shown in section II, there is a relationship between the pigment concentration (C) and water clarity (diffuse attenuation coefficient). The errors associated with CZCS derived optical data refer mainly to near-surface (i.e., one attenuation length (1/K)) measurements, which in terms of K values of interest yields water depths ranging from 10 to 50 m. However, for many practical applications one is concerned with the use of these surface measurements to predict the optical properties to several attenuation lengths. Several of the papers that appear in the bibliography have touched on this problem. Shannon et al. (1985) sounded a warning about the use of satellite-derived chlorophyll data in the region east of Cape Agulhas during the summer owing to the marked subsurface chlorophyll maximum that is beneath the low chlorophyll layer. They also stated that one must be careful in extrapolating CZCS imagery to areas where the algorithms have not been adequately validated.

Straus and Woods (1988), presented comparisons of CZCS derived chlorophyll pigment concentrations with in situ measurements taken on a series of ship cruises from 1984 to 1987 between the Azores and Greenland. The total data set consisted of 20,000 profiles (from 10 m to 200 m). They showed that only a small fraction (5-10%) of the chlorophyll concentration is actually sensed by the CZCS in this region—mainly due to the depth of the chlorophyll maxima. They concluded that the CZCS derived chlorophyll concentrations and those measured from the ship differed by a factor of 2. There is a requirement for both experiments and theoretical modeling to determine the impact of depth variation of pigment concentrations of spectral leaving radiance. The mean in situ chlorophyll concentration of the euphoric zone is overestimated by a factor of nearly 2 in early spring, when the plankton are concentrated near the surface, and underestimated in late summer, when the plankton are concentrated in a layer deep in the seasonal thermocline. They claimed their main source of error (differences as large as a factor of 3 or 4) arose from the fact that the algorithms used for the CZCS could not correct for horizontal and seasonal variation in subsurface chlorophyll—both in chlorophyll content and mean concentration in the euphoric zone.

Kitchen and Zaneveld (1990) examined relationships between beam attenuation, absorption, suspended particle concentrations, size distribution, and pigment content. They concluded that the remote sensing algorithms utilized to predict backscattering from chlorophyll concentration were developed using near-surface data and should not be used for the prediction of vertical structure of backscattering. Since the CZCS measures only the upper one or two attenuation length at best, layers below the mixed layer contribute very little to the CZCS surface reflectance. They further stated that the remote sensing/in situ correlations should not be used when one is estimating the performance of LIDAR systems or bioluminescence radiance below the mixed layer. Other investigators such as Mueller and Lange (1989) indicated that the vertical optical structure in the ocean can be predicted by the CZCS radiance values if sufficient prior knowledge of the climatology is known along with continual in situ sampling of the waters. The 1984 California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruise data (Thomas and Strub (1990) and Strub et al. (1990)) shows that in general, the subsurface chlorophyll maximum north of the front is deeper than 20 m over the entire year and probably is never seen by the CZCS.

There are numerous naval and oceanographic applications that depend upon the knowledge of water clarity, such as an airborne laser: for mapping underwater targets, shallow water bathymetry, aircraft-to-submarine communications, (SLCEVAL, 1989a and b) and for potentially measuring vertical sound velocity profile via Brillouin scattering (Hickman et al., 1991). In calculating the performance of such a LIDAR system, one of the key environmental parameters that must be considered is the water diffuse attenuations coefficient (K) and its associated errors. As mentioned throughout this technical note, the best determination of K

derived from satellite ocean color data that one can expect is approximately ±30%. Figure 1 is given to show the effect that an error of this magnitude in K has upon the uncertainty in target depth detection for an airborne LIDAR system as a function of the number of attenuation lengths and various values of K. For instance, assume a LIDAR system has been designed to have a target detection depth (d) capability of 4 attenuation lengths (i.e., kd=4). Then, for a nominal water clarity of $k=0.05\ m^{-1}$, one would expect to detect targets to depths of 80 m. However, referring to Figure 1, the uncertainty of ±30% in K (at $k=0.05\ m^{-1}$) leads to a depth uncertainty of 54 m. This results in a value for the predicted target depth capability for these types of waters of approximately 80 ±27 m.

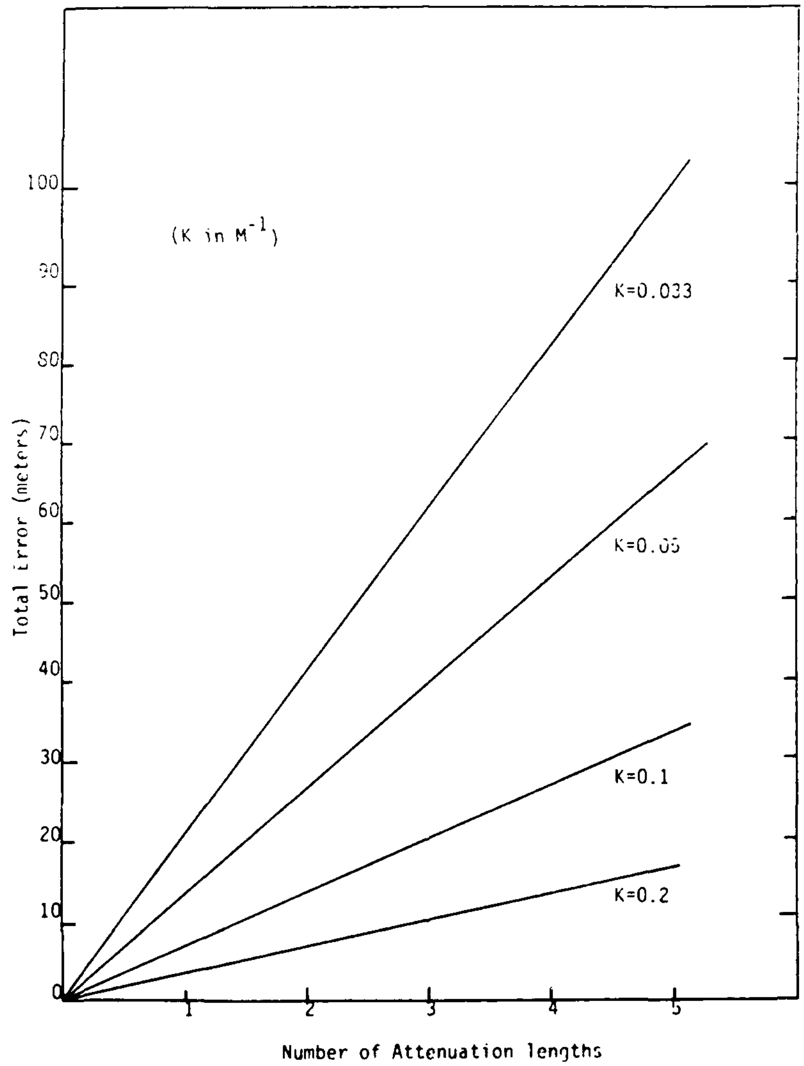

Figure 1. Total error in depth of target detection for an airborne laser system (The error in K is assumed to be ±30%).

III. Sources of Error

Although a great deal of research has been reported on the atmospheric corrections that must be applied to the CZCS data, there has been little mention of the magnitude of the errors associated with other corrections that should be considered. A complete error analysis of the CZCS data has not been made.

The errors associated with the remote sensing of the optical clarity of the water by the CZCS, as listed by the various CZCS investigators, arise from a number of factors such as:

a. atmospheric correction (single scattering or multiple scattering)
b. sensor degradation - changing calibration
c. subpixel sized clouds
d. sensor ringing
e. geographical navigation error (ship and satellite)
f. white caps
g. in situ errors in determination of chlorophyll/pigment concentration
h. contamination of the signal by nonbiological material.

In addition to the above corrections, polarization effects have been ignored. Recent work by Kattawar and Adams (1989) indicates that it may now be possible to take polarizations effects into account and make appropriate corrections. The importance of polarization was discussed in a recent report (EOSAT/NASA, 1986) on Sea-viewing, Wide-Field-of-View Sensor (SeaWiFS).

A brief description of what is known about the atmospheric corrections and sensor degradation is given in section III.A and III.B respectively.

A. Atmospheric corrections

The majority of the images analyzed in the initial papers on the CZCS were atmospherically corrected using Gordon's single scattering model (Gordon and Clark, 1979). Since then investigators in general, have corrected CZCS data using an improved atmospheric correction algorithm which includes multiple scattering (Gordon and Castano, 1987; Gordon et al., 1988; Gordon, 1990). In general it was found that the atmospheric contribution to the upwelling signal detected at the satellite sensor amounted to between 80-90% of the total signal.

Thomas and Strub (1990) and Strub et al. (1990) discussed in great detail a West Coast Time Series (WCTS) of the California Current System (CCS) made using CZCS data from mid 1979 to mid 1986. Due to sensor problems that occurred in 1984 and 1985, the WCTS did not include data for these years. The atmospheric correction algorithm used to process the WCTS data (single scattering) is known to overestimate pigment concentrations at large solar zenith angles present during winter at higher latitudes (32°N) - often >3.0 mg m^{-3} or greater than 3 times higher than found during the 1984 and 1985 winter cruises. For this reason the months of November-February of each year were eliminated from this study. As in several other investigations, the estimate of the total error in comparing CZCS derived pigment concentrations with the in situ data is given as a factor of 2. To date the CCS data set has not been analyzed using Gordon's new multiple scattering atmospheric correction model.

In a recent paper Gordon (1990) included his multiple scattering atmospheric correcting algorithm along with suggestions on changes that can be applied to this algorithm to improve the accuracy of derived optical parameters from future ocean color sensors.

B. Sensor degradation

Gordon et al. (1983b) showed that there had been a general degradation of CZCS sensors starting in 1979. They were able to quantify this degradation by: (1) computing the water-leaving radiance for imagery acquired in regions where the water-leaving radiance was known, or could be independently estimated and (2) by adjusting the sensor calibration to force agreement between the two radiances. The decay of the blue band at 443 nm was found to have decreased to approximately 80% of its initial value by orbit number 20,000 (Sept 1982). In addition, there were fairly large errors associated with this decay factor of ±30-50%. Hovis et al. (1985) performed aircraft measurements to determine the degradation of the CZCS channels. They were able to confirm the major source of degradation was due to loss of reflectance from the large optics that were exposed to the spacecraft environment, namely, the scan mirror and the primary and secondary mirrors of the telescope. They showed that the response of the blue channel (443 nm) degraded approximately 25% over a period of 4 years and 7 months from launch to May 1983. The degradation in the 520 nm band was 3%.

Mueller and Lange (1989) published research on bio-optical provinces stating that there existed a bias of 1.5-2.0 between the CZCS K490 data and in situ measurements. The primary source of this bias error was suspected to be an inaccurate history of the sensor's radiometric sensitivity. Various investigators have stated their interest in performing a full 7-year CZCS time series of the radiometric consistency. There is evidence that not only did the sensitivity of the sensors degrade over the years, but also the CZCS changed its sensitivity at an irregular rate through its operating lifetime.

IV. Preliminary Satellite Error Analysis Model

The analysis of CZCS data to derive phytoplankton concentration and other associated variables has been discussed in sections I-III. A number of articles have pointed out that the atmosphere, instrumental factors, unresolved (subpixel-sized) clouds, sensor calibration changes, as well as the variation of phytoplankton concentrations with depth below the ocean surface, all contribute to the total error budget of satellite derived ocean color parameters. In addition, errors will arise when comparing data acquired on different dates (different sensors, or altered calibrations, different sun angles, different atmospheres) or different scan angles of the same or different images. These errors will be bandpass dependent, which result in even larger errors when more than one band is being used in the analysis. For instance, using a two-band ratio, as used in the present analysis to derive the phytoplankton concentration (C) or the diffuse attenuation coefficient (K), the error will be approximately double the error in one band.

The generic model, which is given in this section, was written for the MS-DOS based personal computer. However, more extensive programs may be written using extended memory that is available in the UNIX version of the mathematical software used. The advantage of a computer model is that many potential cases can be investigated rapidly, so that a parametric envelope for the acquisition of useful data may be developed, resulting in a realistic appraisal of the accuracy of the derived ocean color (phytoplankton concentration) parameter. In this way, an understanding of the anticipated precision of data derived from the CZCS, or from future satellite-borne or airborne sensors may be developed.

The upwelling radiance $Lw(\Theta,\Phi)$ at the satellite sensor is given by equation (4), while Figure 2 is a schematic diagram for a simplified two-dimensional model used to describe the factors used in this equation.

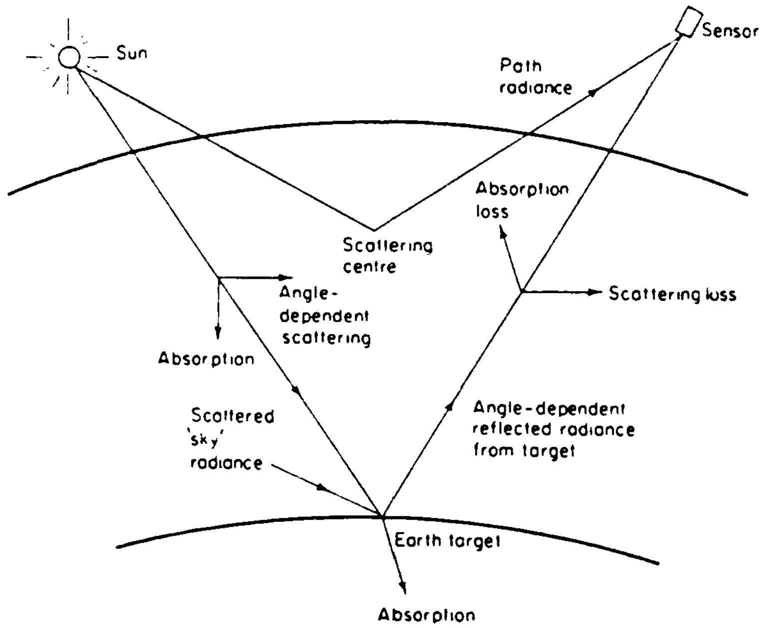

Figure 2. Overall picture of interactions between incident and reflected radiance, the atmosphere, and the Earth's surface.

Input Parameters and Definitions

Calculations of upwelling (water leaving) digital radiance $LW(\phi)$ at the satellite for one channel is given by the following expression

$LW(\phi)$ = sensor gain [solar irradiance X atmospheric transmission for incident and reflected paths X ocean reflectance + atmospheric backscatter] + sensor offset (4)

which becomes

$$LW(\phi) = GA.(E(\Theta).\tau i(\Theta).\tau r(\phi).\rho(\phi) + \Gamma(\phi)) + OF, \quad (5)$$

where the various expressions and values for the parameters follow.

The reflectance of seawater, ρ (ϕ) is given by equation (6), where a 4% reflection coefficient at 500 nm has been assumed for seawater. In addition, a weak view angle dependence has been included.

$$\rho(n) = 0.04 \cdot \exp\left[0.1 \cdot \cos\left[\phi(n) \cdot \frac{\pi}{180}\right]\right] \tag{6}$$

note: $\phi(n)$ = 5(n-12) - view zenith angle in degrees, and degrees are converted to radians
n = 0...24 Counter (running variable)

The atmospheric transmission along the path from the Sun to the Earth's surface is given by equation (7)

$$\tau i(\theta) = \exp\left[\frac{-a}{\cos\left[\theta \cdot \frac{\pi}{180}\right]}\right] \tag{7}$$

where θ is the solar zenith angle in degrees, and a is the extinction coefficient, which has been assumed to be constant over the path length and equal to 0.35.

The atmospheric transmission along the path from the Earth's surface to the sensor is given by equation (8)

$$\tau r(n) = \exp\left[\frac{-a}{\cos\left[\phi(n) \cdot \frac{\pi}{180}\right]}\right] \tag{8}$$

The approximation for the backscatter Γ (n) at the sun zenith angle (0) and view angle (ϕ) is given by equation (9).

$$\Gamma(n) = E(\theta) \cdot \rho(n) \cdot \exp\left[-b \cdot \left[1 + \cos\left[|\theta - \phi(n)| \cdot \frac{\pi}{180}\right]\right]\right] \tag{9}$$

where

$$E(\Theta) = Isol \cdot \cos\left[\theta \cdot \frac{\pi}{180}\right] \quad \text{Irradiance on sea} \tag{10}$$

Isol = Solar irradiance above atmosphere for 0.1 micron wide bandpass close to 500 nm: expressed in W/m^2 (was set equal to 135)

b = constant, which is set to yield the approximate amount of backscatter. It was set equal to 0.4 in the present calculations (amounting to approximately 50% backscatter).

OF = sensor offset (= 2)

GA = Sensor gain for 8 bit quantization (= 80)

Consider the case where the upwelling (water leaving) radiance at nadir view angle ($\phi = 0$ (n=12)) and solar elevation (Θ) of -45. Equation (5) becomes

$$LW(n) = GA \cdot (E(-45) \cdot \tau i(-45) \cdot \tau r(12) \cdot \rho(12) + \Gamma(12)) + OF \tag{11}$$

Assume now a change of 3% error (e1) in the sensor offset (OF) and a 10% error e2 in the sensor gain (GA). Equation (11) now is changed to read

$$LW\epsilon(n) = GA \cdot \left[1 + \frac{e1}{100}\right] \cdot (E(-45) \cdot \tau i(-45) \cdot \tau r(n) \cdot \rho(n) + \Gamma(n))$$

$$+ \left[1 + \frac{e2}{100}\right] \cdot OF \tag{12}$$

The percent change in upwelling radiance with introduction of sensor errors and sun angle and scan angle effects for one channel is given by equation (13)

$$ER(n) = 100 \cdot \frac{LW\epsilon(n) - LW(n)}{LW(n)} \tag{13}$$

The total error in rationing two channels is approximately double that in one channel.

The following calculations shown in Table 1 and Figure 3 give the difference from the radiance from nadir for prelaunch calibration (gain and offset) due to varying view zenith angle and to errors in sensor gain and offset. Here a solar zenith angle of 45° is assumed. Change in solar zenith angle and in atmospheric transmission may yield even larger errors.

These calculations are given only as representative of the type of information that can be derived relatively quickly. Such a modeling technique can be used to perform an absolute error analysis of each source of satellite sensor error. The result is a total error budget for the system.

Table 1. Calculations of radiances and errors associated for various view zenith angles.

View zenith angle	Recorded radiance difference due to view zenith angle and to sensor calibration errors	Resulting error in radiance ratio
$\phi(n)$	$LW\epsilon(n) - LW(n)$	$2 \cdot ER(n)$
-60	-47.675	-30.025
-55	-36.796	-23.174
-50	-27.539	-17.343
-45	-19.452	-12.25
-40	-12.221	-7.696
-35	-5.624	-3.542
-30	0.497	0.313
-25	6.253	3.938
-20	11.726	7.385
-15	16.97	10.688
-10	22.022	13.869
-5	26.902	16.943
0	31.617	19.912
5	36.159	22.772
10	40.509	25.512
15	44.633	28.11
20	48.482	30.533
25	51.986	32.74
30	55.055	34.673
35	57.569	36.256
40	59.368	37.389
45	60.246	37.942
50	59.924	37.74
55	58.027	36.545
60	54.039	34.033

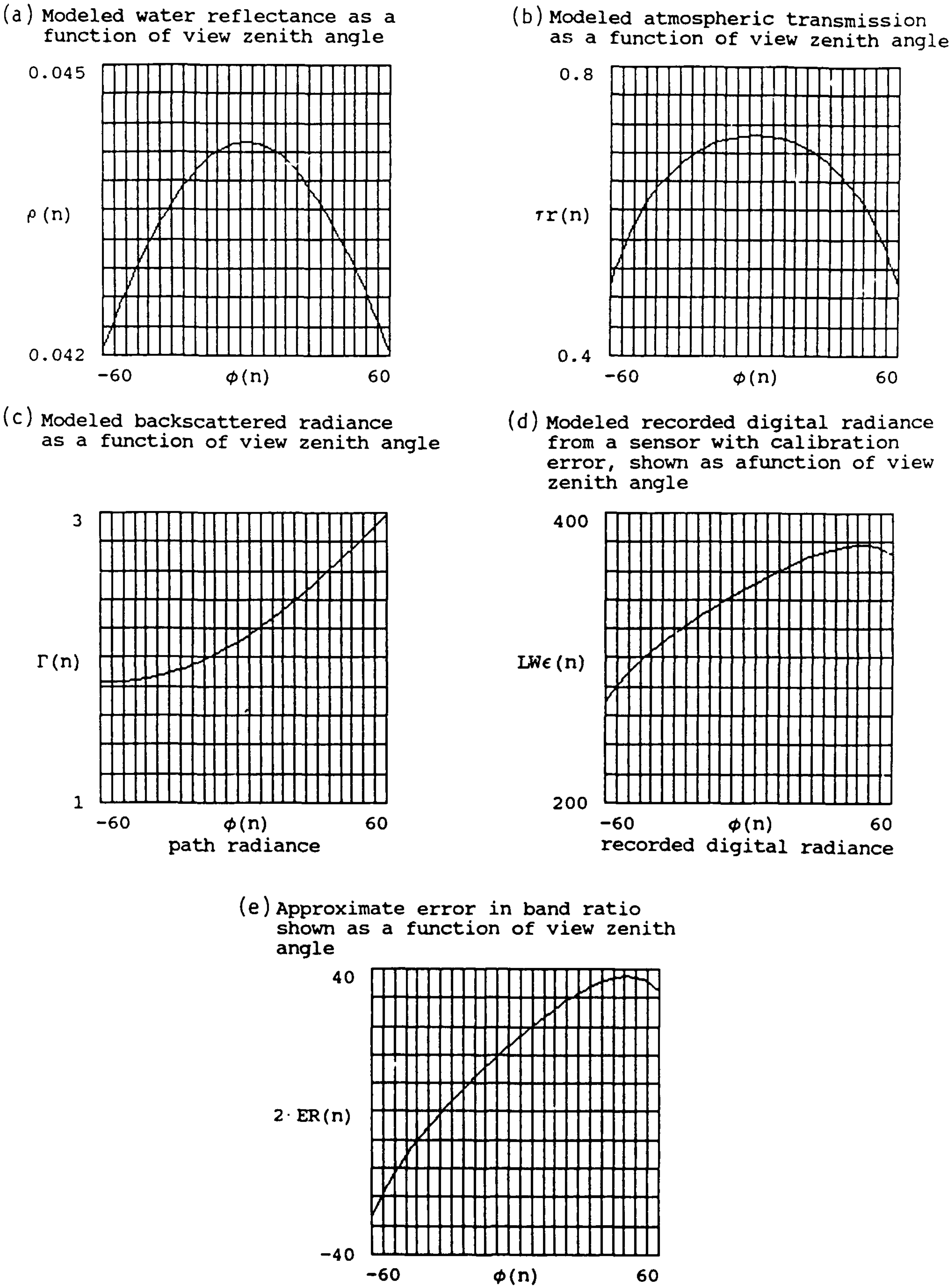

Figure 3. Results of calculations of various parameters affecting the final derived radiance at the satellite.

Image based studies will lead to a knowledge of the variance of recorded radiances over regions in each bandpass. Appropriate theoretical studies will advance our understanding of the impact of such variations on the derived pigment concentrations (C). Further, image band and modeling studies will result in an improved understanding of the impact, for instance, of the atmosphere on the derived values for C. The result is a more accurate assessment of the accuracy of the derived value for C under a variety of bandpasses and imaging conditions. In this way imaging and analysis may be optimized to most accurately map C. In addition, studies investigating the impact of different imaging averaging procedures need to be performed, since quite often the procedure currently followed is to use one pixel in 25 as representative of the radiance instead of averaging the total of 25 pixels in the region. It is well known that the accuracy of index maps, using LANDSAT satellite data, is greatly impacted by the averaging procedures employed.

V. Conclusions and Recommendations

In summary, there are a large number of sources of error that one must consider when using the CZCS images to derive optical properties of the ocean. On a global basis there is general agreement that the pigment concentration, which is directly related to the diffuse attenuation coefficient (K) can be determined from CZCS data only to within a factor of 2, in comparison with in situ measurements. In a much more regional or restrictive area, there is agreement that this error may be reduced to approximately $\pm$30-40%. In order to reduce the error to this magnitude extreme care on making appropriate corrections must be made on a pixel-to-pixel basis. Only a few reports give errors that are this small.

Of particular importance to this summary report are the papers by Strub et al. (1990) and Thomas and Strub (1990), which were mentioned in sections II and III to include a complete time series of the CZCS for the California Current data. A close look at this reference and the techniques used in this analysis should be of real value to additional time series analysis performed on the CZCS data at the Naval Oceanographic and Atmospheric Research Laboratory (NOARL).

It is our recommendation that a modeling program be initiated at NOARL to investigate the total error budget associated with using the CZCS data to derive parameters relating to the surface optical properties of the ocean waters for the various ADI areas. In section IV a generic model for a PC was discussed which could be used to analyze the total error budget. It is emphasized that this is strictly a generic model, which by necessity will become much more complicated.

VI. References

Austin, R. W. and T. J. Petzold (1981). The determination of the diffuse attenuation coefficient of sea water using the Coastal Zone Color Scanner. *Oceanography from Space* edited by J. R. R. Gower, Plenum Publishing, Co. 13:239-256.

Clark, D. K. (1981). Phytoplankton algorithms for the Nimbus-7 CZCS. *Oceanography from Space* edited by J. F. R. Gower, Plenum, New York 227-238.

EOSAT/NASA (1987). System Concept for wide-field-of-view observations of ocean phenomena from space.

Gordon, H. R. and D. K. Clark (1979). Atmospheric effects in the remote sensing of phytoplankton pigments. *Boundary-Layer Meteorology* 18:299-313.

Gordon, Howard R., Dennis K. Clark, James L. Mueller, and Warren A. Hovis (1980). Phytoplankton pigments from the Nimbus-7 Coastal Zone Color Scanner: Comparisons with surface measurements. *Science* 210:63-66.

Gordon, H. R. and D. K. Clark (1981). Clear water radiances for atmospheric correction of coastal zone color scanner imagery. *Applied Optics* 20:4175-4180.

Gordon, H. R., D. K. Clark, J. W. Brown, O. B. Brown, R. H. Evans, and W. W. Broenkow (1983a). Phytoplankton pigment concentrations in the Middle Atlantic Bight: Comparison of ship determinations and CZCS estimates. *Applied Optics* 22(1):20-36.

Gordon, Howard R., James W. Brown, Otis B. Brown, Robert H. Evans, and Dennis K. Clark (1983b). Nimbus-7 CZCS: Reduction of its radiometric sensitivity with time. *Applied Optics* 22(24):3929-3931.

Gordon, Howard R. and Diego J. Castano (1987). Coastal Zone Color Scanner atmospheric correction algorithm: Multiple scattering effects. *Applied Optics* 26(11):2111-2122.

Gordon, H. R., J. W. Brown, and R. H. Evans (1988). Exact Rayleigh scattering calculations for use with the Nimbus-7 Coastal Zone Color Scanner. *Applied Optics* 27(5):862-871.

Gordon, Howard R. (1990). Radiometric considerations for ocean color remote sensors. *Applied Optics* 29(22):3228-3236.

Hickman, G. Daniel, John M. Harding, Michael Carnes, Al Pressman, George W. Kattawar, and Edward S. Fry (1991). Aircraft laser sensing of sound velocity in water: Brillouin Scattering. *Remote Sensing of Environment* (accepted for publication in May or June 1991).

Hovis, Warren A., John S. Knoll, and Gilbert R. Smith (1985). Aircraft measurements for calibration of an orbiting spacecraft sensor. *Applied Optics* 24(3):407-410.

Kattawar, George W. and Charles N. Adams (1989). Stokes vector calculations of the submarine light field in an atmosphere-ocean with scattering according to a Rayleigh phase matrix: Effect of interface refractive index on radiance and polarization. *Limnology and Oceanography* 34(8):1453-1472.

Kitchen, James C. and J. Ronald Zaneveld (1990). On the non-correlation of the vertical structure of light scattering and chlorophyll a in case I waters. *Journal of Geophysical Research* 95(C11):20,237-20,246.

Mueller, J. L. and R. L. Lange (1989). Bio-optical provinces of the Northeast Pacific Ocean: A provisional analysis. *Limnology and Oceanography* 34(8):1572-1586.

Muller-Karger, F. E., C. R. McClain, R. N. Sambrotto, and G. C. Ray (1990). A comparison of ship and Coastal Zone Color Scanner mapped distribution of phytoplankton in the Southern Bering Sea. *Journal of Geophysical Research* 95(C7):483-499.

Satellite Laser Communications Evaluation (SLCEVAL) (1989a). Model description and validation. Naval Ocean Systems Center (Code 844), San Diego, CA.

Satellite Laser Communications Evaluation Algorithm (SLCEVAL) (1989b). Independent validation and verifications (IV and V), final report.

Shannon, L. V., N. M. Walters, and S. A. Mostert (1985). Satellite observations of surface temperature and near-surface chlorophyll in the Southern Benguela region, South African Ocean and Upwelling Experiment, Shannon, L. V. (Ed.) Cape Town: Sea Fisheries Research Institute.

Smith R. S. and K. S. Baker (1978). The bio-optical state of ocean waters and remote sensing. *Limnology and Oceanography* 23(2).

Smith, R. C. and K. S. Baker (1982). Oceanic chlorophyll concentrations as determined by satellite (Nimbus-7 CZCS). *Marine Biology* 66:269-279.

Strass, V. and J. D. Woods (1988). Horizontal and seasonal variation of density and chlorophyll profiles between the Azores and Greenland. Interactions in the World Ocean, D. Reidel., Dordrecht.

Strub, P., James, Thomas Corinne, C. Andrew, and Mark Abbott (1990). Seasonal and non-seasonal variability of satellite-derived surface pigment concentration in the California current. *Journal of Geophysical Research* 95(C7):11,501-11,530.

Thomas, A. C. and P. J. Strub (1990). Seasonal and interannual variability of pigment concentration across a California Current frontal zone. *Journal of Geophysical Research* 95(C8):13,023-13,042.

Walters, N. M., C. J. Kok, and C. Closse (1985). Optical properties of the South African marine experiment, South African ocean and upwelling experiment, Shannon, L. V. (Ed.). Cape Town: *Sea Fisheries Research Institute:*157-170.

Walters, N. M. (1985). Algorithms for the determination of near-surface chlorophyll and semi-quantitative total suspended solids in South African coastal waters from Nimbus-7 CZCS data, South African ocean and upwelling experiment. Shannon, L. V. (Ed.). Cape Town: *Sea Fisheries Research Institute:*175-182.

VII. Bibliography (Pertinent reference articles on the CZCS that have not been discussed in the text.)

Ahlnas, Kristina and Thomas C. Roger (1988). Application of satellite visible band data to high latitude oceans. *Remote Sensing of Environment* 28:985-93.

Austin, R. W., and B. L. McGlamery (1983). Passive remote sensing of optical propagation parameters.' Presented at *32nd Symposium of the AGARD Electromagnetic Wave Propagation Panel on Propagation Factors affecting Remote Sensing by Radio Waves*, Oberammergau, Federal Republic of Germany.

Barale, V., C. R. McClain, and P. Malanotte-Rizzoli (1986). Space and time variability of the surface color field in the Northern Adriatic Sea. *Journal of Geophysical Research* 91(C11):12,957-12,974.

Deschamps, P.Y., M. Herman, and D. Tanre (1983). Modeling of the atmospheric effects and its application to the remote sensing of ocean color. *Applied Optics* 22(23):3751-3758.

Gordon, Howard R. (1976). Radiative transfer: a technique for simulating the ocean in satellite remote sensing calculations. *Applied Optics* 15(8).

Gordon, Howard R. (1989). Can the Lambert-Beer law be applied to the diffuse attenuation coefficient of ocean water. *Limnology and Oceanography* 34(8):1389-1409.

Gordon, H. R. and D. K. Clark (1980). Remote sensing optical properties of a stratified ocean: an improved interpretation. *Applied Optics* 19:3428.

Gordon, H. R. (1987). Calibration requirements and methodology for remote sensors viewing the ocean in the visible. *Remote Sensing of Environment* 22:103-126.

Gordon, Howard R., Otis B. Brown, Robert H. Evans, James W. Brown, Raymond C. Smith, Karen S. Baker, and Dennis K. Clark (1988). A semi-analytic radiance model of ocean color. *Journal of Geophysical Research* 93(D9):10,909-10,924.

Kiefer, Dale A. and Roswell W. Austin (1974). The effect of varying phytoplankton concentration on submarine light transmission in the Gulf of California. *Limnology and Oceanography* 19(1-3):55-64.

Kiefer, D. A., R. J. Olson, and W. H. Wilson (1979). Reflectance spectroscopy of marine phytoplankton. Part 1. Optical properties as related to age and growth rate. *Limnology and Oceanography* 24(4):665-672.

Leventuev, V. P. (1990). Model calculations of the atmospheric effect on ocean water color. *Soviet Journal of Remote Sensing* 7(1):72-82.

Morel, Andre and Louis Prieur (1977). Analysis of variations in ocean color. *Limnology and Oceanography* 22(4):709-722.

Morel, Andre (1980). In-water and remote measurements of ocean color. *Boundary Layer Meteorology* 18:177-201.

Morel, Andre (1988). Optical modeling of the upper ocean in relation to its biogenous matter content (Case I waters). *Journal of Geophysical Research* 93(C9):10,749-10,768.

Morel, Andre and Jean-Francois Berthon (1989). Surface pigments, algal biomass profiles, and potential production of the euphotic layer: Relationships reinvestigated in view of remote-sensing applications. *Limnology and Oceanography* 34(8):1545-1562.

Mueller, J. L. (1984). Effects of water reflectance at 670 mm on Coastal Zone Color Scanner (CZCS) aerosol radiance estimates off the coast of Central California. *Proceedings of SPIE, Ocean Optics VII*, Monterey, CA.

Quenzel, Heinrich and Martina Kaestner (1980). Optical properties of the atmosphere: Calculated variability and application to satellite remote sensing of plankton. *Applied Optics* 19(8):1338-1344.

Sid'ko, A. F. (1990). Correlation of spectral radiance and phytoplankton content in the ocean. *Soviet Journal of Remote Sensing* 74:585-599.

Simpson, J. J. (1990). On the accurate detection and enhancement of oceanic features observed in satellite data. *Remote Sensing of Environment* 33:17-33.

Smith, Raymond C. and Karen S. Baker (1981). Optical properties of the clearest natural waters (200-800 nm). *Applied Optics* 20(2):177-184.

Smith, R. C. (1981). Remote sensing and depth distribution of ocean chlorophyll. *Marine Ecology Progress Series* 5:359-361.

Smith, R. C. and W. H. Wilson (1981). Ship and satellite bio-optical research in the California Bight. *Oceanography from Space* edited by J. R. G. Gower, Plenum, New York p. 281.

Stockel J. A., J. L. Mueller, H. Pak, and D. Menziers (1986). Data from the optical dynamics experiment (ODEX) R/V Acania expedition of 10 Oct through 17 Nov 1982, vol. 1: CTD and optic profiles, data report NPS-68-86-013, Naval Postgraduate School, Monterey, CA.

Viollier, M., D. Tanre, and P. Y. Deschamps (1980). An algorithm for remote sensing of water color from space. *Boundary-Layer Meteorology* 18:247-267.

Wroblewski, J. S., Jorge L. Sarmiento, and Glenn R. Flierl (1988). An ocean basin scale model of plankton dynamics in the North Atlantic 1. Solutions for the climatological oceanographic conditions in May. *Global Biogeochemical Cycles* 2(3):199-218.

Wroblewski, J. S. (1989). A model of the spring bloom in the North Atlantic and its impact on ocean optics. *Limnology and Oceanography* 34(8):1565-1573.

Distribution List

Office of Naval Technology
Attn: Mr. Glen Spalding
Room 907
800 N. Quincy Street
Arlington, VA 22217-5000

Space and Naval Warfare Sys. Com.
Attn: CAPT Carl Hoffman (PMW-141)
LCDR William Cook (PMW 141D)
Mr. L. Fabian (PMW 183-4)
Mr. Max Houck (PMW-185K)
2511 Jefferson Davis Highway
Washington, DC 20363-5100

Chief of Naval Operations
Department of the Navy
Attn: Dr. Art Bissom (OP-02T)
Mr. R. Lauer (OP-021T2)
Mr. F. Hashimoto (OP-021T2)
Washington, DC 20350-2000

Dr. Wayne Esais
Code 971
NASA/GSFC
Greenbelt, MD 20771

Dr. George Kattawar
Department of Physics
Texas A&M University
College Station, TX 77843-4242

Dr. Howard R. Gordon
Department of Physics
University of Miami
Coral Gables, FL 33124

Naval Ocean Systems Center
Attn: Dr. G.T. Kaye, Code 844
Dr. Rod Buntzen, Code 7501
San Diego, CA 92152-5000

Naval Underwater Systems Center
Attn: Mr. Dave Williams, Code 61
Newport, RI 02841-5047

Dr. Michael Duggin (25)
308 Bray Hall
CESF
State University of New York
Syracuse, NY 13210

Technical Director
Naval Oceanography Command
Stennis Space Center, MS 39522-5001

Office of Naval Research
Ocean Science Directorate
Attn: Dr. C. Mobley, Code 11230P
Dr. R. Spinrad, Code 1123
Mr. Marvin Blizard, Code 11250A
800 N. Quincy Street
Arlington, VA 22217

Dr. James L. Mueller
Center for Hydro-Optics and
Remote Sensing
San Diego State University
San Diego, CA 92182

Oceanographer of the Navy
Chief of Naval Operations
Attn: CDR Jon Malay, OP-961E2
Mr. Don Montgomery
U.S. Naval Observatory
34th and Massachusetts Ave., NW
Washington, DC 20392-1800

NOARL Code 100
115
125L (10)
125P
200
215 (3)
300
311
320
321 (40)
330
331
333

REPORT DOCUMENTATION PAGE

Form Approved
OBM No. 0704-0188

1. Agency Use Only (Leave blank).

2. Report Date.
March 1991

3. Report Type and Dates Covered.
Final

4. Title and Subtitle.
Accuracy of Ocean Color Data Derived from the Coastal Zone Color Scanner (CZCS)

5. Funding Numbers.
Program Element No. 63704N/0603714D
Project No. 0101/F[illegible]
Task No 100
Accession No. DN258120
DN259069

6. Author(s).
G. D. Hickman, S. C. Gallegos and M. J. Duggin*

7. Performing Organization Names(s) and Address(es).
Naval Oceanographic and Atmospheric Research Laboratory
Ocean Science Directorate
Stennis Space Center, Mississippi 39529-5004

8. Performing Organization Report Number.
NOARL Technical Note 116

9. Sponsoring/Monitoring Agency Name(s) and Address(es).**
Space and Naval Warfare Systems Command
Washington, DC 20363-5100

10. Sponsoring/Monitoring Agency Report Number.
NOARL Technical Note 116

11. Supplementary Notes.
*State University of New York   **Advanced Underwater Acoustic Modeling Project Office

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract (Maximum 200 words).

The U.S. Navy is interested in investigating the use of ocean color data for naval applications, as they apply within the Air Defense Initiative. The major source of available data for assessment is the Coastal Zone Color Scanner (CZCS) data base. These data were collected during 1979-1986. Although the CZCS is no longer operational, much information has been published on the analysis of the data. This technical note reviews that literature, which deals primarily with the measured and estimated errors associated with using the CZCS data to derive either chlorophyll concentrations (C) or the diffuse attenuation coefficient (K) of oceanic waters.

The recognized uncertainties in the absolute values of the quantities of C and K must be taken into account when addressing the potential use of CZCS data for certain naval applications. The literature generally agrees that on a global basis, K or C can be determined from CZCS data to only within a factor of 2, as compared with in situ measurements. In addition, the water-leaving radiance for one spectral band can probably be obtained from the CZCS data, but in a more regional or smaller geographical area, after corrections to within 15%. This percentage relates to an error approximately 30% in K or C, both of which use a ratio of at least two spectral bands. Extreme care must taken in applying the appropriate corrections on a pixel-to-pixel basis if the error is to be reduced to this value. If the concern is with only spatial trends of water clarity at a particular point in time or with temporal trends at each point in space, the CZCS images can probably be used; however, the conditions under which they apply must be indicated.

14. Subject Terms.
Optics, Data Base, Satellite

15. Number of Pages.
17

16. Price Code.

17. Security Classification of Report.	18. Security Classification of This Page.	19. Security Classification of Abstract.	20. Limitation of Abstract.
Unclassified	Unclassified	Unclassified	SAR